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Analysis of the Potential of Biogas Production from Animal Manures for Small Scale Renewable Electricity in Nigeria

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Abstract: In the 21st century, rural energy is the key to a good standard of living and sustainable economic development. Nigeria has been facing a serious economic destitution ever from the beginning of the unpredictable fluctuations in crude oil prices in the international market. The country solely depends on oil for foreign earnings and relies predominantly on fossil fuels for power generation. Biogas for power generation is one of the many approaches to a cleaner production of electricity. The Nigerian government has demonstrated a profound curiosity to diversify the nation's economy through investment in agriculture which requires electricity to promote sustainable development. Therefore, this study presents a prospect for the utilization of biogas (methane (CH_4)) for electricity generation in Nigeria. The application of biogas for energy generation offers an opportunity for onsite power generation in remote rural communities of developing countries. In this study, a biogas potential of 19.176 million m^3CH_4/year was estimated with an electricity production capacity of 29 billion kWh from animal residues based on available data from livestock production in Nigeria in 2016. Furthermore, a total of 64.3 Gg CH_4 emission which is equivalent to 1.607.5 Gg of Carbon dioxide (CO_2) and expected to be saved via anaerobic digestion was estimated.

Key words: Biogas, energy, emissions, manure, renewable, Nigeria

INTRODUCTION

Biomass is a basic source of renewable energy to meet the future low carbon energy demand. Biogas is the gas produced from wet biomass, either in anaerobic digesters or in landfills by capturing naturally occurring methane. The development of biogas for rural power generation is an integral part of clean development mechanism in the context of cleaner production. Cleaner production has been implemented in different regions due to increasing environmental challenges (Geng *et al*., 2010). The production of electricity through the use of renewable and sustainable technologies is part of the integral approaches to implement technology transfer initiatives and promote the adoption of cleaner technologies (Costa-Junior *et al*., 2013; Dovi *et al*., 2009). The development of renewable energy systems, based on clean power supply in economically challenged geographical locations has occupied a focal point of interest in recent years (Mclellan and Corder, 2013; Zhai *et al*., 2014). Biogas solutions in biorefineries could represent a key technology to improve sustainability (Hagman *et al*., 2018). Biogas produced by anaerobic digestion of organic waste offers distinctive benefits compared to other renewable energy sources by addressing environmental challenges associated with organic waste management and creating electricity generation potential (Govender *et al*., 2019). Esteves *et al*. (2019) explored the use of biogas from manure in an environmentally beneficial means of power generation and production of biofertilizers. Climate change mitigation remains a key focus for national and international government agencies including stakeholders in the energy sector. Energy-related activities should be developed in such a way as to boost the mitigation of anthropogenic GHG emissions (Lin *et al*., 2017). Utilization of biomass for energy applications is a fundamental issue in the context of sustainable development. Sustainable development is the norm of meeting the present needs of human development objectives without compromising the ability of natural systems to meet future needs. Future energy security and environmental sustainability issues are the main driving forces for improving biomass utilization (Naqvi *et al*., 2018) for the purpose of energy generation. In rural areas of developing countries, energy plays a vital role as a major factor in domestic economic productivity. The cost of energy production directly affects goods and services

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as well as the quality of life. Currently, Nigeria faces a challenge of energy crisis, mainly due to insufficient power generation. Expectedly, the country's energy demand profile has continued to rise in the last few decades due to increasing socio-economic needs.

The present electrification scheme in the country conspicuously depends on grid extension (Mohammed *et al*., 2017). Nevertheless, grid extension is not an economically promising option for the electrification of rural communities in developing countries due to a high cost of investment in transmission and distribution infrastructures. The extension of grid power networks to rural areas is an economically threatening task taking into consideration the restrictions of complex rural terrains, extended distances and severe transmission losses. As a consequence, some rural households rely on expensive diesel-powered generators for their energy whereas the investment cost for a small biogas digester unit could provide a better substitute for rural energy demand (Mohammed *et al*., 2017) and aid to reduce environmental hazards (Afazeli *et al*., 2014). Perhaps, the use of biogas for energy production in rural areas presents sufficient opportunities for a possible energetic stability and a significant contribution to the production of environmental sustainability (Seadi *et al*., 2008; Karaca, 2018). According to Moller *et al*. (2008), the production of biogas from anaerobic digestion is one of the most cost-effective approaches for GHG reduction.

Biogas production can be achieved from a variety of biodegradable sources. Biodegradable substances are biological materials with different capabilities which undergo bio-decomposition with the help of micro-organisms to breakdown the organic materials in the absence of oxygen to release biogas. Biogas is a combustible methane-rich gas. Biogas obtained from waste is a good source of energy for power generation and production of useful heat energy. Biogas can be produced from a variety of waste sources such as animal manure, wastewater, commercial and industrial wastes, biodegradable institutional garbage, lignocellulosic biomass from crop residues and landfill materials. Technologically, biogas can be obtained from co-digestion, dry fermentation and thermochemical gasification. Nigeria has strong potential for the production of biogas. Many developing countries like China and India have installed large numbers of small-scale biogas tanks in rural energy communities. Rural communities where biogas systems are installed could derive the benefit of minimizing environmental pollution in addition to production of organic fertilizer. Berhe *et al*. (2017) presents the structure of the institutional arrangement of biogas application for energy production. In the framework, the structural system focuses on the strategic steps in the dissemination process of biogas plants. Szymanska and Lewandowska (2015) studied biogas power plants in Poland with focal points on structure, capacity and spatial distribution. The structure presented in the study largely utilizes disperse systems using a single source of bio-waste feedstock. Renewable energy development in Nigeria has gained prominent awareness in recent years but quite a little has been achieved towards investment in biogas for rural electrification. Therefore, this study presents the strategic prospect for biogas development based on some selected animal manures for cleaner production of electricity in Nigeria. It also presents an integrated structure of Biogas Combined Heat and Power (BCHP) for rural electrification.

MATERIALS AND METHODS

Proposed structure of biogas for rural electrification in Nigeria: The use of biogas for power generation in rural areas benefits a nation in numerous ways. This is because it is one of the means to promote the development of power generation assets, especially, in developing countries where there is limited access to the electrical grid. Rural electrification through biogas energy technologies offers innovative sources of income for farmers and enhances local economic development while preserving a clean environment and a high quality of life that helps keep rural areas habitable for the dwellers. In Nigeria, there are varieties of feedstock for biogas production: food processing waste, livestock dung, poultry waste, crop residues as well as other materials such as aquaculture wastewater, seaweed and filamentous algae. Other feedstock includes spent straw, cane trash, hay, sugar-cane bagasse, seafood-processing wastewater, yard waste and plant stubble. Biogas anaerobic digesters can be installed for slaughterhouses, industrial waste, biodegradable municipal waste, human excreta and animal dung. A biogas system for power generation consists of three components: digester (fermentation tank), gas holder and internal combustion engine. The digester could be a waterproof cylindrical container or a cube-shaped structure having a cove through which a fermentable mixture of the biodegradable liquid slurry is introduced into the digester. The gas holder is typically an airproof container that cuts off air to the digester by the process known as anaerobiosis and collects the gas produced. In a typical design of a biogas production system, the digester is usually designed with an overflow pipe to allow the sludge to move into a drainage ditch while the gas holder is equipped with a gas outlet for delivery to the internal combustion engine. Figure 1 shows an integrated structure of biogas for Combined Heat and Power (CHP). The structure largely represents a co-digestion of waste substrates which is the most appropriate treatment for biowaste: biomethanization and

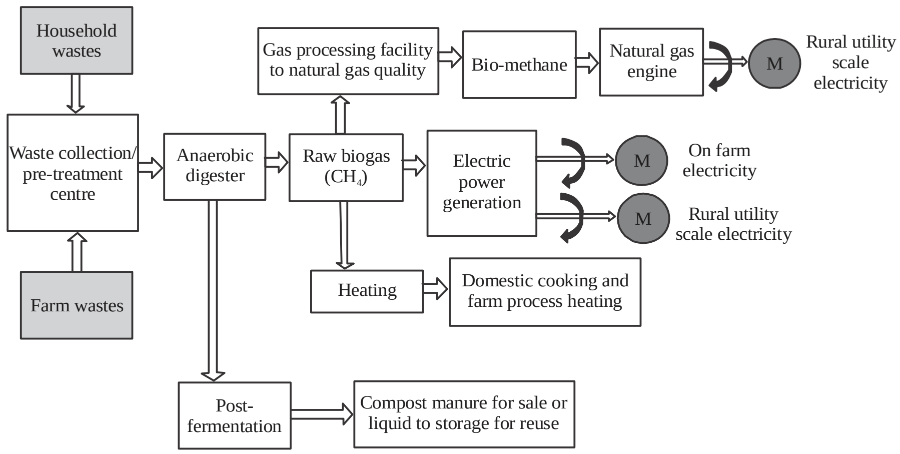

Fig. 1: Integrated structure of Biogas Combined Heat and Power (BCHP) for rural electrification

composting. Anaerobic co-digestion of biomass waste has been reported to improve the cumulative yield of biogas than mono-digestion (Otun *et al*., 2015; Oliveira *et al*., 2015). It also captures the biomethanization upgrading approach for the production of natural gas from biogas. The proposed structure is a sustainable biomethanization plant that converts biowaste into high-purity biogas for electric power generation or cogeneration of heat and power and compost for agricultural applications.

Construction materials for biogas digesters in rural areas in Nigeria: The economics of the design and construction of a biogas digester for power generation is very essential. The important criteria that must be put into consideration in the design and construction process are the availability of waste materials and the volume of gas required for power generation. In Nigeria, economic challenges place limitations on the affordability of rural dwellers to use the modern biogas system, especially, digesters. Therefore, digester reactors could be constructed using some locally available materials such as cement, steel, brick and concrete. Utilization of these local materials could satisfactorily alter the normal engineering construction principle, the economics of technology and the shapes of the digester reactors. In this case, rural skills in clay brickwork and plastering craft could also be useful.

Livestock production in Nigeria: Nigeria is the most populous country in Africa with great potential for agricultural production. Nigeria is currently on progression to a state of a self-enclosed agricultural production country in the world. Livestock production in Nigeria is one of the most important aspects of the nation's agricultural sector. Most rural households in Nigeria profoundly depend on livestock production to boost their local income. In the focal point of this study, the 2016 Food and Agricultural Organization (FAO) statistics of the United Nations on live animal production were used for the analysis. Table 1 shows the data on livestock production quantity in Nigeria.

Table 1: Livestock production quantity in Nigeria (FAO., 2016)

Types of animal	Population
Cattle	20,560.933
Poultry	148,404.000
Goat	73,879.631
Pig	7,488.631
Sheep	42,091.042

Determination of manure production from selected livestock manures: This segment focuses on the production of manure from selected animals. The 5 fully mature animals were selected from each category of livestock of the local animal species. Each of the 5 animals was confined to a separate barn slot at the animal research facility of the Federal Polytechnic Nasarawa in Nigeria and they were fed with the same quantity of their feedstuff for a day. The produced manure was collected and weighed after 24 h. The average quantities of total manure produced by each category of the selected animals are calculated as follows: cattle = 26 kg, Pig = 2.9 kg, Sheep = 1.82 kg, goats = 1.75 kg and poultry = 0.09 kg. Figure 2 shows the category of animal manures used for the study.

Estimation of biogas production and energy potential from animal manures: A mature livestock, especially, cattle, produces a substantial amount of faeces on a daily basis, usually once every 2 h or less. In rearing of animals, manure production simply gives the farm manager a tipoff of the performance of the digestive processes. Animals that produce good quality manure based on normal colour and good content are usually considered healthy by nutritionists. Good quality manure yields biogas with a better quality of methane

Pig waste | Cattle dung | Goat excreta | Sheep excreta | Poultry manure

Fig. 2: Category of animal manure samples used for the study

Table 2: Indices of the Number of live animals (N_{LA}), the Quantity of manure produced (Q_{MP}), the Manure availability coefficient (M_{AC}), the Ratio of the total solid concentration in the manure (R_{TSC}) and the Quantity of estimated biomethanization potential (Q_{EBP})

Types of livestock	N_{LA} Population	Q_{MP}* kg manure/head/day	M_{AC} (Afazeli *et al*., 2014) kg/kg	R_{TSC} (Abdeshahian *et al*., 2016) gTSC/100 g	Q_{EBP} m^3/kgTSC
Cattle	20,560.933	26.00	0.5	25	0.6 (Afazeli *et al*., 2014)
Poultry	148,404.000	0.09	0.5	29	0.8 (Afazeli *et al*., 2014)
Goat	73,879.631	1.75	0.5	25	0.4 (Afazeli *et al*., 2014)
Pig	7,488.631	2.90	0.5	25	0.22 (Kemausuor *et al*., 2014)
Sheep	42,091.042	1.82	0.5	25	0.4 (Kemausuor *et al*., 2014)

*Field work

gas. Anaerobic digestion is a sustainable option for the effective management and stabilization of biodegradable waste. Biogas is produced by biochemical reactions of an anaerobic process with about 55-70% methane (CH_4), 25-45% Carbon dioxide (CO_2) with other constituent gases such as sulphur, hydrogen sulphide, oxygen and water. Biochemically, the production of animal manure is a function of digestive performance, feed and water intake as well as rumen fermentation. Besides, the theoretical potential of biogas production from manure depends on the number of live animals, the quantity of manure produced, the total solid concentration in the manure and the bio-methanization potential of the manure feedstock. In this study, the formulation for estimating the theoretical potential of biogas production from animal manure is presented in Eq. 1. Table 2 presents the indices of the Number of live animals (N_{LA}), the Quantity of manure produced (Q_{MP}), the Manure availability coefficient (M_{AC}), the Ratio of the total solid concentration in the manure (R_{TSC}) and the Quantity of estimated biomethanization potential (Q_{EBP}). Rearing of animals in Nigeria is largely on free-range during the day but majority of them are confined at night. Therefore, the choice of 0.5 for M_{AC} as presented in Table 2 is based on the assumption that manure can be recovered in the middle of the day. The potential of the Thermal Energy Value (TEV) and Electricity Production (EP) from biogas using a gas engine was calculated using Eq. 2 and 3, respectively.

$$TPBP_{(manure)} = N_{LA} \times Q_{MP} \times M_{AC} \times R_{TSC} \times Q_{EBP} \quad (1)$$

Where:

- $TPBP_{(manure)}$: Theoretical potential of biogas production from manure
- N_{LA} : Number of live animals
- Q_{MP} : Quantity of manure produced
- M_{AC} : Manure availability coefficient
- R_{TSC} : Ratio of the total solid concentration in the manure
- Q_{EBP} : Quantity of estimated biomethanization potential

$$\text{Thermal Energy Value (TEV)} = TPBP_{(manure)} \times CV_{Biogas} \quad (2)$$

where, CV_{Biogas} = Calorific values of biogas. CV_{Biogas} is the lower heating value of the unit biogas which is 21.5 MJm^{-3} (Hosseini and Wahid, 2014; Garcia, 2014). To calculate the EP, $TPBP_{(manure)}$ and η_{engine} are used as shown in Eq. 3 where, η_{engine} denotes the overall conversion efficiency of biogas engine to electricity. The value of η_{engine} varied with different electric power plants. A value of 25% has been used in small electric power engines and a range of 35-42% in large turbine systems (Hosseini and Wahid, 2014; Benito *et al*., 2015). In this study, 25% is assumed for η_{engine}:

$$\text{Electricity Production (EP)} = \eta_{engine} \times TEV/3.6 \quad (3)$$

Emissions reduction: Decomposition of animal manure is one of the biogenic sources of GHG emissions. GHG emissions from animal residues vary significantly by type, feed intake and growth status. The freshly deposited manure contains methane which is due to the enteric fermentation of microbes in the stomach of the ruminant animals and the anaerobic degradation of the volatile solids by bacteria actions. The global warming potential of methane and carbon dioxide can affect climate change via. atmospheric oxidation reactions and interface with infrared energy. Free emission of GHGs into the atmosphere is one of the contemporary challenges confronting our global society. Manure management through biogas production is one of the most effective ways to abate free emissions of GHGs from animal waste into the atmosphere. When animal manures are dumped in open places, they undergo aerobic biological decomposition, resulting in less methane gas production compared to the anaerobic digestion process. The methane gas produced escapes freely into the atmosphere. Biogas production systems can be used to prevent unrestrained emissions of methane into the atmosphere. The uncontrollable emission of methane gas has a high heat-trapping potential in the atmosphere compared to carbon dioxide but has a shorter atmospheric lifetime. Therefore, the emission reduction of livestock manure application for biogas production is calculated using Eq. 4 (Inter-Governmental Panel on Climate Change, 2006; Guo, 2010). The Global Warming Potential (GWP) of CO_2 is 25 times that of methane (Inter-Governmental Panel on Climate Change, 2006; Ozsoy and Alibas, 2015). The expected CO_2-emission reduction based on the CH_4 emission is also calculated:

$$\text{Methane Emission, } ME = EF_T\,(\text{kg/head/year}) \times N_{LA}\,(\text{head})/10^6\,(\text{kg/Gg}) \quad (4)$$

Where:

EFT : Emission factor for animal category (kg/head/year)

N_{LA} : Number of live animal (head)

RESULTS AND DISCUSSION

Biomass feedstocks in animal manure have been found to be viable for the sustainable production of biogas in anaerobic digestion facilities. According to the 2016 livestock production data, Nigeria has 20,560.933 cattle, 148,404.000 poultry, 73,879.631 goats, 7,488.631 pigs and 42,091.042 sheep as shown in Table 1. The highest potential of manure is generated by cattle and it also made the foremost contribution to biogas production. The total manure expected to be produced in 2016 was approximately 35,482 Mt. The theoretical potential of biogas from the animal manure in the same year under consideration is approximately 19,176 million m^3 as presented in Table 3. The electricity production capacity of 19,176 million m^3 CH_4 is estimated to be 29 billion kWh. Consequently, this electrical capacity of biogas for energy generation presents a substantial role of livestock manure as a determinant source of renewable energy in Nigeria.

Apart from carbon dioxide, methane is the main source of GHG in the agricultural sector. The biochemical decomposition of animal manure in open sites leads to emissions of methane and carbon dioxide. Emissions of methane and carbon dioxide account for a significant share in the total emissions of GHGs orchestrating from agriculture with damaging ecological impacts. Currently, dairy farmers are becoming increasingly aware of the impact of their activities on the environment and the impacts on climate change (Asselin-Balencon *et al*., 2013), since, emissions of hazardous gas are suspected to be generated when the manures are not used in a sustainable manner, therefore, evaluating the anticipated emission reduction potential of the manure is very important. It was estimated that as much as 4% of global warming is due to methane emissions from waste (Asselin-Balencon *et al*., 2013; Ramos *et al*., 2006). It has also been stated that manure is the second largest source of GHG emissions in dairy farms (Aguirre-Villegas and Larson, 2017). The application of anaerobic digestion for the treatment of animal manure in rural areas could help to save methane emissions that are expected to be released from unconfined sites. In addition, the combustion of biogas in electric power systems is a better way to control GHG emissions compared to the direct burning of animal waste to obtain heat energy in the open space three-stone stoves that are commonly used in rural areas of Northern Nigeria. The emission factors used in this study are based on values for tropical African countries: pig = 2 kg/head/year, cattle = 1 kg/head/year, goat = 0.22 kg/head/year, sheep = 0.21 kg/head/year and poultry = 0.023 kg/head/year (Arthur *et al*., 2011). The estimated methane emission savings from animal manure is presented in Fig. 3. A total of 64.3 Gg CH_4-emission which is equivalent to 1,607.5 Gg CO_2-emission is expected to be saved through the use of the manures for energy generation in 2016.

Table 3: Estimation of the quantity of manure and theoretical potential of biogas production

Types of livestock	N_{LA} Population	Q_{MP} kg manure/head/day	Manure available Mt/year	$TPBP_{(manure)}$ Mm^3CH_4/year
Cattle	20,560.933	26.00	24.390	14.634
Poultry	148,404.000	0.09	707.000	566.000
Goat	73,879.631	1.75	5.899	2.360
Pig	7,488.631	2.90	991.000	218.000
Sheep	42,091.042	1.82	3.495	1.398
Total			35.482	19.176

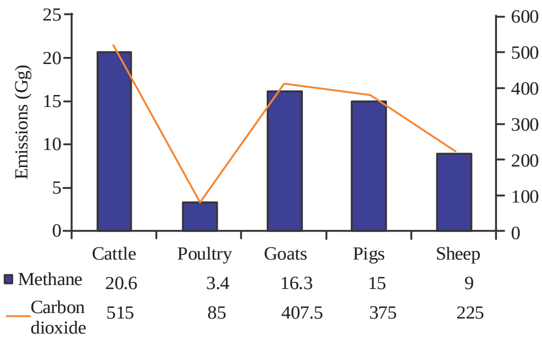

Fig. 3: Methane and carbon dioxide emissions from livestock manure

CONCLUSION

This study evaluates the prospects for utilization of biogas from animal manure for cleaner production of electricity in Nigeria. The analysis presented in this study provides useful information on the potential of biogenic waste from animal manures for biogas production in Nigeria. The results show a suitable theoretical potential for generating biomass energy via the anaerobic digestion approach. Biogas projects could be enhanced in the country to replace the excessive use of wood fuel and charcoal consumption in rural areas. At the rural household level, production and utilization of biogas from animal manure could reduce the effect of the energy crisis that is widely experienced in the country by improving the availability of electrical energy for domestic consumption. Renewable energy development represents suitable systems to mitigate emerging global climate change orchestrating from the global energy sector. Apart from benefitting the country in ways that increase the potential for rural energy independence, there are many other advantages to the efficient development of biogas for power generation which include the following:

- Fnancial diversification for energy stakeholders and rural inhabitants through investments in rural communities
- Support for local agricultural processing activities and reduction of demand for commercial fertilizers
- Creation of jobs for local craftsmen, technicians and engineers
- Production of economically useful waste by-products with substantial economic values
- Support for the development of rural infrastructure and provision of flexible and reliable electricity in rural areas
- Conversion of energy-rich waste materials into useful energy and preventing them from reaching landfills which has serious potential GHG emissions

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